

Woodman S, Hiden H, Turner M, Dowsland S, Watson P.

**Monitoring of Upper Limb Rehabilitation and Recovery after Stroke: an
Architecture for a Cloud-based Therapy Platform.**

In: 2015 IEEE 11th International Conference on eScience. 2015, Munich: IEEE

DOI: <http://dx.doi.org/10.1109/eScience.2015.29>

Copyright:

© 2015 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works.

DOI link to article:

<http://dx.doi.org/10.1109/eScience.2015.29>

Date deposited:

16/12/2015

Monitoring of Upper Limb Rehabilitation and Recovery after Stroke: an Architecture for a Cloud-based Therapy Platform

Simon Woodman, Hugo Hiden, Mark Turner, Stephen Dowsland and Paul Watson
School of Computing Science

Newcastle University, Newcastle upon Tyne, UK

simon.woodman@ncl.ac.uk, hugo.hiden@ncl.ac.uk, mark.turner@ncl.ac.uk, stephen.dowsland@ncl.ac.uk, paul.watson@ncl.ac.uk

Abstract—Amongst the therapies available to stroke sufferers, one that is gaining attention is the application of video games to encourage therapeutic movement. The Limbs Alive project at Newcastle University has developed a system that gathers therapeutic game data from patients, uses statistical tools to estimate a number of performance metrics and presents the results to patients and clinicians via web applications. This paper describes the architecture of this system and outlines the various technical challenges that were overcome, including in security and deployment.

I. INTRODUCTION

Approximately 120,000 people suffer a stroke annually in the United Kingdom alone. It is the leading cause of disability [1], with around 900,000 people living with the consequences of stroke. The increase in survival rates mean that, while 70% survive and regain the ability to walk, the recovery of upper limb function is still poor with less than 20% of sufferers regaining enough dexterity to be independent [2]–[5]

Studies have shown, however, that significant improvements in upper limb function can be achieved but only with intense, repetitive practise of rehabilitation movements. [6]. Limited resources, though, particularly the availability of trained therapists, have meant that guidelines have not been developed on the requirements for practice.

In attempt to address this and provide a platform to motivate patients to perform the repetitive movements required for rehabilitation and to capture the results of these practise sessions, the Limbs Alive project has developed a number of video games that mimic movements developed by experienced therapists [7]. As such a platform is, by its very nature, data and computationally intensive a system to collate, process and present the data to both clinicians and patients has been developed. This paper describes the design and performance of this system, which has been built upon the e-Science Central (e-SC) Cloud Analytics platform [8]. The general pattern of usage is for a patient who suffers a stroke and who has been deemed suitable for inclusion within the initial study to be issued with a laptop containing a copy of the rehabilitation game and equipped with a 3G communications dongle. After initial training, the patient is then encouraged to play this game regularly and data is automatically uploaded to the

platform described in this paper for processing, distribution to clinicians and creation of feedback for the patient. This system architecture is illustrated in Figure 1, which shows the deployment of the various components of the platform.

In addition to the transfer of data from the game laptop to the data processing platform, provision is also made to retrieve configuration settings from the central server. This data can include information such as player meta-data, messages from the clinician managing that patient (including goals and play targets) and also control signals that can remotely disable the game in the event of a medical requirement (i.e. a ‘kill switch’ to prevent a patient from performing potentially harmful activities).

e-Science Central has been used in many projects [9]–[11] of which some have custom user interfaces but the interface required for Limbs Alive was the most complex that has been developed to date. The application described in Sections VI and VII has no state or data storage of its own - everything is provided e-Science Central which the application accesses via APIs. Both the functional and non-functional aspects of e-Science Central were key to the project - workflows were able to efficiently integrate disparate technologies such as Java, C# and R; elastic compute could deal with the bursty workloads when new models were generated; the security model isolated patient’s data, and provenance tracked the results to inspire confidence in the data generated [12]. As will be described in the paper, all of these combined to minimise the amount of custom code necessary to develop the application.

II. RELATED WORK

A number of applications of e-Science and related GRID technologies to the healthcare sector have been reported. These are frequently concerned with the capture and storage of data and its subsequent sharing with expert users who will collaborate to produce a diagnosis – for example the eDiamond project [13] was particularly successful in sharing X-Ray images for breast cancer treatment. This was an early example and made heavy use of tools such as Globus [14], but the principle is similar to the system described in this paper. Another medical data sharing application is the TeleDICOM remote medical collaboration platform, which is the result

of an EU project [15] and is used to share and annotate DICOM images, which are a widely adopted standard within the medical imaging field.

In other fields, projects such as DAME [16] gather data from aircraft engines via remote links and present this to technicians via a Signal Data Explorer [17] that allows pattern recognition tools to be used to diagnose unusual engine operation. Whilst an engineering application, the principles of remote data collection coupled with centralised expert analysis are closely aligned with the aims of this project.

The use of computer games to aid rehabilitation following a stroke has been actively pursued by other groups [18]. Many, in fact, use the Kinect sensor from Microsoft to track an individual's movement. Owing to ethical and accuracy concerns about putting what is, in effect, a camera into a patient's home, our approach was to use controllers designed to report position in three dimensional space. Other projects offer rehabilitation environments but do not track progress or feature the record keeping and analytics featured in our project [19].

III. FROM CONTROLLERS TO CLINICIANS

The Circus Challenge game runs on a laptop which is issued to the patient by their clinician. The laptop is pre-configured as described in Section VI and uses either a wifi-dongle or the patient's broadband to access the internet. An internet connection is required for the game to send data to e-Science Central for processing which enables the clinician to monitor a patient's progress remotely. The overall architecture is shown in Figure 1.

The controllers used in the Circus Challenge game are Sixense TrueMotion controllers (a forerunner of the Razer Hydra)¹ which give their position, relative to a base station, in three dimensional space. As the patients play the game their movements are interpreted to ascertain whether they have passed through waypoints which compose signature moves designed to aid their rehabilitation. Moves include a sawing action, twisting a bottle top and raising your arms above your head.

From a high level perspective there are three separate types of file generated during a session:

- PRD** Profile data for the patient. Contains a list of levels completed, high scores, counts of successful gestures etc. Updated once per session.
- PLD** PlayData for the individual mini-games. Contains date and time information, score for that level, elapsed time within the level etc. Created once per session.
- SRD** Movement data for a CAHAI assessment (a clinical measurement of upper limb movement following a stroke). Contains the raw waypoint success and failure information for the moves within the assessment game (40 moves).

The Circus Challenge game can be separated into two parts: firstly the main 'game' which is actually comprised of 10

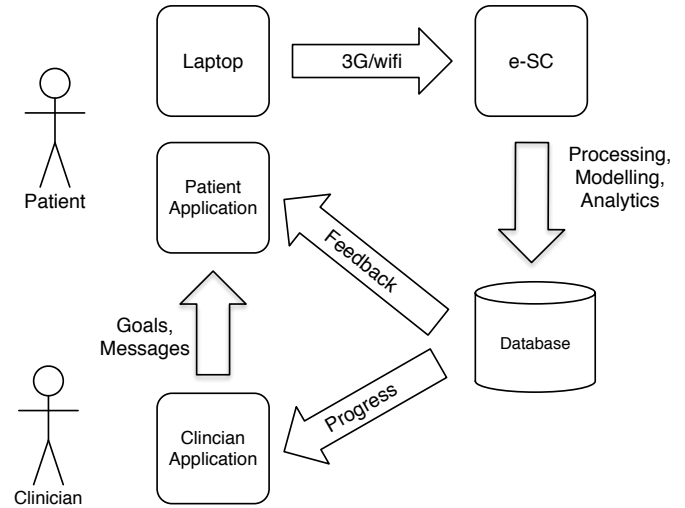


Fig. 1. Data process

mini-games each containing up to 10 moves and featuring a different element of circus skills; and secondly, the 'assessment game' in which the patient must attempt all 40 moves. The moves have been carefully selected to represent the range of movements required for everyday living. When playing the game, the character on screen will perform a trick or stunt if the patient successfully completes the move (for example a complex juggling routine). If the patient does not complete the move successfully the character will mimic them by not performing the trick correctly, for example, dropping the balls. During the assessment game the patient has the ability to retry a move if s/he is unsuccessful.

When a patient plays one of the mini-games from the main game an updated Profile (PRD) file and one PlayData (PLD) file is generated. When the patient plays the assessment game, the SRD file is generated, storing much finer grained information about the movement of the patient (3D data (X,Y,Z position) and quaternions sampled every 10 ms during the move for each hand). Although individuals will vary significantly (discussed further in the goals section) patients are encouraged to play the main game for 30 minutes per day and play an assessment game once per week. This is analogous to the frequency at which the research patients were manually assessed.

At the end of each session (patients are instructed to close the game when they finish playing it) the files which have been generated are uploaded into e-Science Central and stored in their raw binary form within the user's homepage. Following that, various processes are run on the files dependant on which type of file has been uploaded.

The PLD files contain information about each mini-game which was played in a proprietary binary format. A workflow processes each of these files, converts the binary to XML and then extracts parts of the XML to be stored in e-Science Central DataSets within the patient's homepage. One row in the DataSet is created for each attempt at each level of

¹<http://sixense.com/>

the mini-game. This will include the time and duration of the attempt and the score and rating achieved. In addition to this, a summary DataSet is updated with the total time played, average time played and the date of the last time the player played a game. The former data is used to give detailed feedback to the clinician about how and when the patient is playing the game (many short bursts or fewer longer sessions) and how they are progressing through the levels. Given that each level has particular moves associated with it, it is possible to determine whether a patient is continually struggling with a particular move. The latter information provides a brief overview to the clinician in the context of this and other patients they are monitoring.

The processing of the PRD files is very similar to that of the PLD files, except the data is inserted into different DataSets and used for different purposes. The PRD files contain high score information and game achievements which are stored in DataSets within the patient's homespace. These are used as motivational tools and are displayed on a website which the patient may log in to. The PRD files also contain a record of how many times, and for how long, the patient has made specific moves within the game.

Perhaps the most interesting processing pipeline occurs when a patient plays the Assessment game. As described above, this is intended to be played once per week and is used to calculate the progress, in rehabilitation terms, of the patient. At the end of the session when a patient plays the Assessment game a number of SRD files will be uploaded into e-Science Central. These contain high resolution data describing the movement of the controllers in three dimensional space. From this movement it is possible to calculate whether or not the controllers (and thus the patient's hands) moved through waypoints which represent the signature moves of the game and if so, how smooth and synchronised they are. The movement data is ingested into an e-Science Central workflow which has three objectives:

- 1) Convert the binary SRD files into text based ones which can be processed in R
- 2) Calculate the CAHAI score from the R-based model
- 3) Update the DataSets with the patient's assessment

The Chedoke Arm and Hand Activity Inventory (CAHAI) [20] is a validated upper-limb measure that uses a 7-point quantitative scale in order to assess functional recovery of the arm and hand after a stroke. As part of the project a linear regression model was generated in R to calculate a CAHAI score based on the moves within the assessment game. The model was built from kinematic variables such as speed, smoothness and synchrony against clinically derived CAHAI-9 scores [21]. As the project continued, the model was refined to also take into account all previous assessments which had been carried out. From a technical perspective, the workflow in e-Science Central was required to manage the interoperability of code developed in different languages by members of the project. The predictive model was developed in R, many of the core data manipulation blocks required were developed in

Java, and the code to parse and cut the waypoint data was developed in C#.

One of the contributions of e-Science Central to the project was the ability to deal not only with ongoing data acquisition but also process historical data. This was required when the CAHAI model was updated in order to update the scores for each patient based on the new model. As all of the movement data from previously completed Assessment games was stored in e-Science Central, it was possible to write a workflow which scaled out and processed all previous data with the new model. Concurrently, any new data arriving would be automatically queued and processed with the new version of the model when capacity was available.

IV. SECURITY MODEL

In any application, and particularly in situations where personal data is collected, the security of the information held in a system is critical. Because this application is built upon the e-Science Central platform, which in turn inherits its security model from the GOLD project [22], the access control adopted is based upon the concept of users being categorised into a number of roles. The roles that a user belongs to define what parts of the system they can use and what actions they are both allowed and expected to perform. We define three distinct roles for users:

- | | |
|----------------------|--|
| Patient: | If a user is in the patient role, s/he will play the games, upload data and update the summary datasets owned by the clinician. |
| Clinician: | Represents medical professionals whose job it is to manage a number of patients. Clinicians are allowed to add and remove patients in response to their clinical workload. |
| Adminis-
trators: | Administrators operate the system and can add/remove and also move patients between clinicians if required. |

Patients, clinicians and managers are created using workflows, which are responsible for creating the e-Science Central users, defining datasets that are used to contain summary data (e.g. play statistics, CAHAI model results etc) and setting the correct access control lists (ACLs) on all of the new objects. The fundamental principle underlying the security model is that patients own their own data within the system. By adopting this approach, we make use of the default e-Science Central behaviour in that all data uploaded by a user is only visible to that user unless provision is explicitly made for another user to have access.

Each patient has a private data storage folder that is used as a staging area for data uploaded by the game. Once raw game data files are processed, the results are placed into e-Science Central datasets owned by the patient that have a permission set on them that allows the supervising clinician to read their contents.

Before a patient is provided with a copy of the game, his/her supervising clinician first creates a patient record (which is represented as an e-Science Central user) from the Clinician Application described in Section VI. This is done by workflow

which creates an account, adds the newly created user to the group of patients that the Clinician is responsible for and creates the empty datasets that are used to contain the various summaries for that patient. As part of the creation process, the clinician is required to enter some basic details that allow the correct processing to be performed. This is represented as Metadata attached to the patient record and includes attributes such as age, arm length, date of stroke etc. Once this has been performed, the patient is provided with an e-Science Central username and password which is used to configure the game. From this point on, each time any data is uploaded via the API or any processing workflows executed, these are performed under the patients account following the principal of least privilege [23].

In order to efficiently generate summary tables for groups of patients, each clinician has a summary dataset that contains high level results from each patient. Part of the workflow that processes the uploaded game files also therefore has to update this summary dataset. In order to do this, whilst still providing a separation between patients, each patient is given a permission to ADD data to this summary dataset but not to view or otherwise edit its contents. Patients are also members of a patients group owned by their clinician. This group membership is used as the basis for creating patient lists on the clinician facing website.

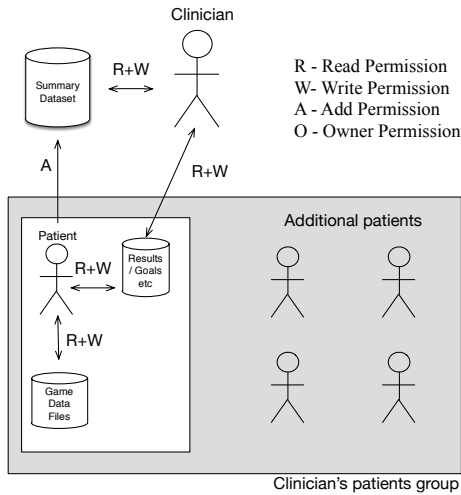


Fig. 2. File and dataset permissions

Clinicians are granted read access to the datasets containing the processed game data for a particular patient and read/write access to the datasets containing the list of goals for a given patient. This read/write access is required for clinicians to be able to specify and modify goals such as total play time for their patients. These goals are then displayed on the patient facing website along with progress indications.

There is the potential for patients to be transferred between clinicians – either permanently or if their progress is to be reviewed independently. This can be achieved by adding a patient to the patients group owned by the new clinician and

by granting the relevant permissions on the patients datasets. Transferred patients will then be visible on the new clinician's summary dashboard as the patient lists are generated using the patients group owned by the clinician.

V. DATA STORAGE

In its original incarnation, e-Science Central only supported data stored using a simple immutable file based metaphor. Attempts to append or modify files in e-Science Central result in a new version of that file being created and appended to the version history. This model, while suitable for many applications, is problematic for situations where data is being collected continuously from devices (such as game installations) with a requirement for immediate processing and display.

In order to address this, e-Science Central has been expanded to accommodate the concept of datasets, which are collections of non-relational tables that can be appended to over time. Data can be inserted into datasets as rows of JSON data and implementations are available which store this data either as a table within a PostgreSQL database or as collections within a MongoDB installation. By exposing this functionality via the e-Science Central platform, the same security model underpinning the existing data, code and workflow storage can also be applied to dynamic collections of data. A dataset within e-Science Central consists of a number of dataset Items, which can each hold a specific type of data (Figure 3):

- Multiple row** A table of data containing multiple rows of observations. This maps closely to a spreadsheet format and the format of data passed as data-wrappers between workflow blocks.
- Single row** A single row of data that is updated whenever new data is written to it.
- Single value** A single numerical piece of data that is updated whenever it is written to.

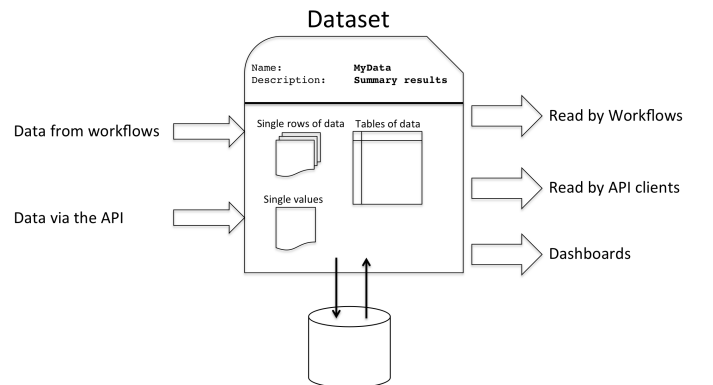


Fig. 3. Structure of an e-Science Central dataset

A. Multiple row items

Multiple row items (Figure 4) are represented as continuously expanding tables. Each piece of data added to them is

X	Y	Z	C
10.2	53.53	100.25	35
13.4	34.12	210.54	50
21.4	11.44	150.21	40
15.8	25.10	140.35	65
34.1	98.31	298.52	12

Updates added to the end of the table

Data table grows over time

Fig. 4. Adding rows to a multiple row item

appended to the bottom of the table, with data being sorted in order of addition date.

In addition to the actual data contained in a row, each row of data contains **timestamp** and **id** fields which are used internally for querying and modifying data. Workflow blocks and dashboards can, for example, query multiple row items for all of the data falling within a specified date range. Multiple row items do not have any updating logic associated with them other than to keep on adding new data to the end of the data table. Each row of data within a multiple row item is stored as a row in the main e-Science Central database as a JSON formatted string. Multiple row items are used in this application to store records of player progress, estimates and actual measurements of CAHAI scores and for storing and tracking goals.

B. Single row and single value items

Single row and single value items are stored as single JSON objects and single numerical values respectively within the database. Single row items can therefore contain a number of distinct key:value pairs whilst single value items only store a single piece of data. Single items within e-Science Central can have different update strategies in place, which dictate how these values behave when updated with new data (currently, updates can calculate a cumulative sum, a rolling average, a rolling maximum/minimum or directly replace the existing data). Single items are used within this application to keep track of the total game play time, average scores, average play time and the current CAHAI predicted value. These are updated each time games are played and provide an efficient mechanism for accessing frequently used data in order to display summaries on the clinician and patient websites.

VI. CLINICIAN APPLICATION

Within the project two new web applications were developed for use by the clinicians and patients. Neither of these groups used e-Science Central directly and all of their interactions with it were through web applications developed specifically for their needs. These applications used the API provided by e-Science Central for user management, data storage and processing.

A. Patient Management

At any one time a clinician will be responsible for several patients, each at different points in their rehabilitation. The application enables clinicians to manage the progress of each

of their patients, by providing summary information with the ability to dive quickly into more detail where needed. The clinician can centrally control the ability of the game to upload data into e-Science Central on a per patient basis.

1) *Registering Patients*: Patients are registered in the system by their clinician. The application assumes that the patient is already known to the clinician, and exists in some other management system, and has a unique reference number which is understood by the clinician. Thus, no Personally Identifiable Information is stored within the system. Other information required by the predictive CAHAI model is also collected, such as age in years, gender and side of hemiplegia. The clinician is responsible for setting a password for the patient. This password is used by the patient to log into the patient application, and by the game to log into the e-Science Central API in order to upload data.

2) *Monitoring Patients*: After login clinicians are shown a dashboard view of their patients, drawing their attention to important upcoming events' either new messages or patient reviews. Patient reviews are split into two lists, upcoming reviews and overdue reviews. Upcoming reviews are defined as those which are due within the next three days, overdue reviews are those that are one day or more past the patient review date.

The list of patients is designed to give a high level indication of how each patient is doing. The clinician can quickly check performance indicators such as average play time, the date the patient last played the game and his/her current CAHAI score. The list can be sorted and searched to allow the clinician to quickly find patients of interest.

From the patient list the clinician can select any patient profile and get finer grained information. The patient profile is split into three sections, overview, progress and gameplay. The overview shows the information entered when the patient record was created, as well the extra fields required by the predictive CAHAI model. These may or may not have been available when the patient was registered within the system. However, they must be entered prior to the patient playing an Assessment game as the model requires them. Once the required data is present, the clinician is able to activate the patient's account which will enable data to be uploaded from the game.

The progress section displays previous CAHAI scores as either a bar chart or a table. The tabular view allows for paging through data, sorting on any column and string search across the whole table. This is useful if the clinician is looking for the score on a particular date or wanting to see assessments of a certain type. CAHAI scores have two types, manual and calculated. A manual assessment is done by the clinician in the patient's home or during a hospital visit and comprises of a series of scored activities that provide sub-scores for the total CAHAI score. A calculated score is generated by the CAHAI model in an e-Science Central workflow. Both assessment types appear on the bar graph but are coloured differently to highlight their origin to the clinician.

The gameplay section shown in Figure 5 allows the clinician

to delve down into performance data on individual levels during a play session. The clinician is presented with a table containing a row for every week the patient has been playing. These are given week numbers as a reference for the clinician but also start dates for that week to give chronological ordering. Totals for the number of days that week the patient has played, total number of individual gameplay sessions as well as totals for levels and games are shown. Selecting a row triggers it to slide open and reveal a daily break down of the play that week. The information is now sub-divided into days. The final level of detail is reached by opening up a specific day, revealing a list of all the levels attempted by the player that day, along with scores, start and end times, duration and difficulty.

Week	Week Beginning	Total Sessions	Days Played	Total Duration	Total Levels	Total Games Played
40	29/12/2014	5	1	00:04:09	5	2
41	05/01/2015	33	4	00:27:14	33	8
42	12/01/2015	68	5	01:26:32	68	8
43	19/01/2015	55	4	01:28:02	55	5
44	26/01/2015	6	2	00:05:38	6	4
45	02/02/2015	52	5	00:41:08	52	8
46	09/02/2015	41	5	00:41:06	41	8
47	16/02/2015	20	3	00:26:05	20	7
48	23/02/2015	41	6	01:11:23	41	9
49	02/03/2015	10	2	00:14:10	10	4

Fig. 5. Patient gameplay

3) *Reviewing Progress*: A patient is reviewed every week by default but the clinician has the opportunity to manually set the next review date at the end of each review. The review process comprises the following six steps:

- 1) **Patient Overview** – The patient’s summary information to refresh the clinician’s memory of the patient
- 2) **Progress** – The progress measured by the different assessments (such as CAHAI) done since the last review
- 3) **Current Goals** – A list of the current completed and outstanding goals the patient has been assigned
- 4) **New Goals** – A chance for the clinician to modify and set new goals for the patient
- 5) **Messages** – The clinician can enter a message to encourage the patient
- 6) **Review** – A confirmation page displaying all the information from the previous steps and next review date for the clinician to confirm

Each step is shown to the clinician in turn, allowing him/her to move forward and back through the steps. The review process is designed to be simple and as quick as possible without compromising the ability of the clinician to take in all the information needed to make decisions about the patient.

B. Assessment Management

In order for clinicians to understand the progress of their patients they need to be able to add manual assessments following a visit from a therapist to the patient and view them alongside the calculated assessments generated by workflows detailed in Section III. The assessment types supported within

the system are commonly collected by the therapists within the project. Note that some of these assessments are generic and not all were collected for each patient. That said, the system is capable of storing them (including the subsection scores) and provides a facility to track the progress made by the patient.

- **CAHAI-9** The Chedoke Arm and Hand Activity Inventory. A quantitative scale used to assess functional recovery of the arm and hand after a stroke [20].
- **FMA** Fugl-Meyer Assessment of Motor Recovery after Stroke. Evaluates and measures recovery in post-stroke hemiplegic patients [24].
- **MOCA** The Montreal Cognitive Assessment. A paper based test to detect Mild Cognitive Impairment [25].
- **MAS** Modified Ashworth Scale. A measure of muscle spasticity in patients with neurological conditions [26].
- **EHI** Edinburgh Handedness Inventory. A measure of the dominance of a person’s dominant hand [27].
- **NIH** National Institutes of Health Stroke Scale. A measurement used to quantify the impairment caused by stroke [28].

The Fugl-Meyer assessment is particularly challenging given the calculation of an overall score involves ~50 sub-scores across seven categories. Some of the categories are only assessed if certain criteria are met (a score above a threshold earlier in the test). For all of the assessments, the clinician can save a partial assessment and return later to complete it. Notes can also be added to record the situation of the patient at the time of assessment (to explain a poor score for example). Assessments which have been entered manually within the application can also be edited to address mistakes.

C. Goals

The clinician portal enables the clinician to set goals for patients to complete on a periodic basis. This encourages prolonged practise and aims to provide patients with a suitable reward depending on their individual needs.

1) *Viewing Previous Goals*: The clinician can see at a glance all of the patients s/he has set goals for along with some high level statistics, simple counts of how many goals patients have been set, how many they have passed and how many they have failed. In a similar manner to that presented in the game play data, selecting on a patient row reveals more detailed information about each goal and the controls for removing and editing them. Each goal has a start and end date between which the patient must try to achieve that goal, a goal type, the name of the game the goal applies to and finally the target of the goal.

Some goals, particularly those based around the time spent playing, may be reached across multiple gameplay sessions. In such cases, a progress bar showing the percentage of the goal being completed is shown. This can help the clinician in different ways. If the patient only just misses out on a target the patient may only need gentle encouragement. If the patient achieves the goal far too early the clinician knows to make the next goal much harder. Conversely, if a patient is a long way from the target then the clinician can investigate as to why. It

could be something outside the game causing difficulty, or it could be that the goal is too hard for that patient.

2) *Setting New Goals:* Depending on what aspects of a patient's performance s/he is interested in, the clinician can adjust the creation of new goals for that patient. All goals have start and end dates as well as a frequency. The dates provide a window during which the goal must be reached by the patient. The frequency is either weekly or daily and dictates how frequently the goal is reset. Figure 6 shows the method for creating a new goal for a patient.

Fig. 6. Creating a new goal

If the clinician sets start and end dates two weeks apart and chooses a daily frequency, the patient must reach that goal every day for 14 days. By choosing weekly, the goal would only have to be reached twice in that period. A new goal can apply to all or a specific game. Different games have different therapeutic moves in them, so a patient with a specific movement weakness can be given goals for games that contain moves to help with that weakness. Each goal can be one of three types:

- 1) Play Time
- 2) Total Score
- 3) Minimum Level

The target changes depending on the type selection made by the clinician. Targets for play time are always in minutes, total scores are integers that are realistic scores given with the game and minimum level is between one and ten for each difficulty level.

The clinician application provides a simple portal for clinicians to both manage and assess their patients. Day to day patient management is done through the registration of new patients onto the system and their weekly review. Clinicians can delve through all the data collected about a patient to inform their ongoing assessment or research work.

VII. PATIENT APPLICATION

The patient application serves as a portal for patients to monitor their progress and to read supporting material in order to set up and use the game.

The different aspects of the patient's progress that can be accessed through the patient application include games/levels completed, goals achieved or currently working towards and achievements made by progression through the game.

The supporting material within the application provides details on how to set up the game and its related hardware, navigate the options menus and getting the game started. There are also step-by-step instructions for each of the games.

The patient application is primarily intended to be used by patients themselves but could also be used by a friend or relative, especially in regards to the Support Section. With this intended audience in mind, the interface has been built to be as simple as possible to promote the content of the application to users whilst not overwhelming them.

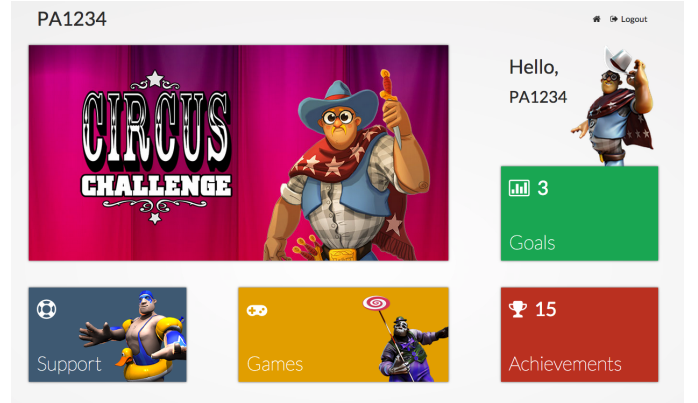


Fig. 7. Patient application home screen showing simplified user interface

A. Goals

The goals section identifies to the user goals that are currently active. Progress towards meeting a particular goal is shown as a percentage and timeframe is shown in relative terms e.g. Achieve a total score of 3000 before Tuesday. Showing only active goals and using relative time are two techniques used to help remove visual clutter from the application and improve the ease of use for the user.

B. Games

The gameplay section is divided into two stages. The first stage presents the user with a grid of games that are available within the application. The games that are available to play are shown in colour, and the games that are not currently available are greyed out to indicate that they are not selectable.

Clicking on an available game will take the user to a game summary screen, shown in Figure 8. This screen shows in detail the user's progress through the selected game. At the top of the screen there is a progress bar that shows the user's progress through the current difficulty level. Summaries are shown to indicate the current difficulty the user is progressing through, total time played, average play time and when the user last played. The remainder of the screen shows the user's attainment on each level on each difficulty. Users are shown the top star rating and high score they have achieved for each level. Difficulties that have not yet been unlocked are unavailable, which is denoted by a closed padlock symbol.

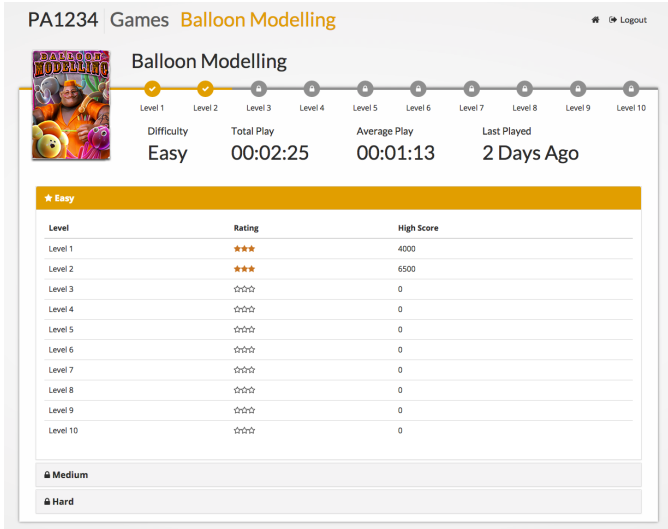


Fig. 8. Individual game summary screen

C. Achievements

This section, shown in Figure 9, presents users with a graphical representation of their progress in terms of the achievements gained. There are multiple sections on the page. There is a section for achievement in the game in general, and sections for each of the different games available.

Each section shows graphical icons to represent the achievements that are available. Achievements yet to be unlocked are shown as greyed out, achievements unlocked are shown in colour. This is useful as it shows the user at a glance what has been completed and what is still left to complete. Hovering over any of the icons will reveal a tooltip that contains descriptive text for that achievement. Using a tap action on touch-enabled devices can also activate the tooltip. Each section on this page also shows general progress in each of the games towards unlocking achievements, for example in the Balloon Modelling games you see a counter for the number of models made, balloons burst and balloons released. General progress towards unlocking all achievements in each section is visualised as a progress bar.

D. Support

The support section of the portal is split into five general sections; Getting set up, Navigating the menus, Starting the Game, Movements and Game instructions.

The five sections represent logical partitions in the support literature. This approach makes what would be a relatively large, impenetrable body of text more digestible for the user.

Text size controls have been provided in the support section to aid low vision users.

E. Further Ideas

A useful addition to the patient application would be a leaderboard section that allows patients to see how their progress compares with others. There are ethical issues to consider for this feature in terms of impact on the morale of

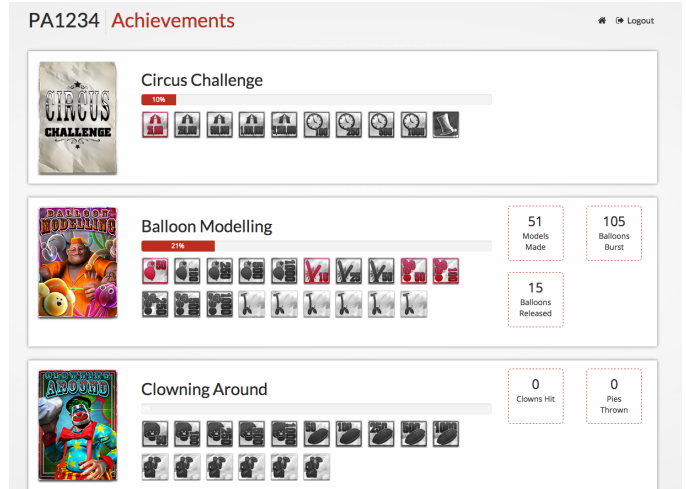


Fig. 9. Patient achievements

those who are not performing as well as others. This disparity in performance may be down to the fact that stroke patients suffer varying impacts on their mobility due to the severity of their strokes, and may not represent actual progress made.

With this in mind the implementation of a leaderboard would ideally be based around a metric that measures effort rather than attainment. The patients would be split into groups or leagues so that they are competing against other patients who have suffered a comparable level of mobility loss. Whilst appropriate metrics such as 'total time played' existed we decided against offering patients the ability to compare themselves to others because of the ethical and motivational factors.

VIII. SYSTEM DEPLOYMENT AND USAGE

During the use of this platform (2013–2014), configured laptop computers containing the game installation, an e-Science Central API client library and 3G communication dongle were distributed to 49 users. An e-Science Central account was created for each of these users, who were in turn assigned to their clinician as described in Section IV. During this time, data was collected from each of these systems, uploaded, processed using a number of e-Science Central workflows and the results stored within the patient and clinician data sets.

A. Data upload volumes

During the execution of the study, a total of 10 GB of raw movement data was collected for the set of patients, averaging approximately 200 MB per patient. This is illustrated in Figure 10, which shows the data volume uploaded per user sorted by the most active individual.

However, Figure 10 also demonstrates that the raw data uploaded was not distributed evenly across the cohort, with a number of patients generating less than 50 MB of data. During this deployment, the system was still in a prototype phase and there were a number of issues with data upload reliability and processing errors. It is likely that a more fully

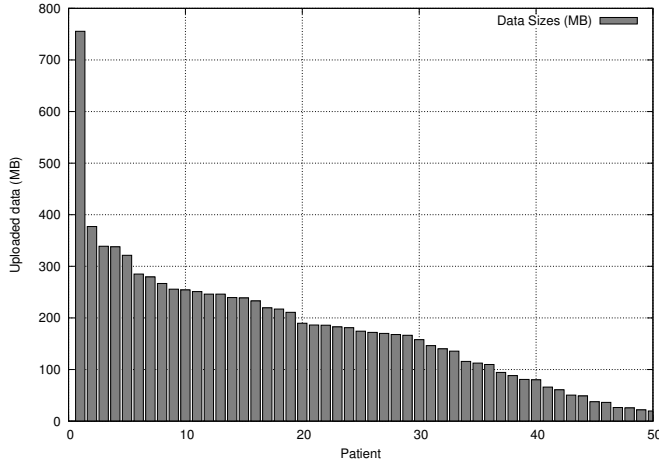


Fig. 10. Uploaded data size/patient

developed system would shift the distribution of usage shown in Figure 10, and would therefore generate an additional storage requirement. This variability of both usage and storage was a strong influence in the decision to deploy the system on a cloud infrastructure and the elastic nature of the resources available means that additional usage and storage can be catered for.

B. Uploaded data processing requirements

Over the course of its deployment, the installation processed 541 assessment games, the processing of each of which took an average of 84.5 seconds (Figure 11).

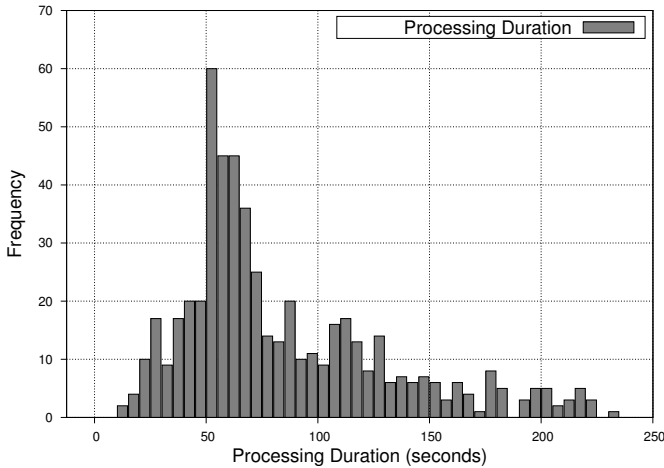


Fig. 11. Processing workflow durations

Additionally, the processing shown in Figure 11 was not evenly distributed across the entire cohort. Again, if a more fully developed version of the system were to be re-deployed, it is likely that more of the cohort would interact with the system for a longer period and impose a greater computational load. The use of the cloud and the e-Science Central platform gives a degree of protection here as the system has

demonstrated the potential for operation at significant scale in previous projects [10].

C. Additional processing

The results shown above only reflect the processing and storage requirements for data dynamically uploaded by the laptops distributed to the patient cohort. A significant number of other processing tasks are also performed in order to capture and maintain the system and the results datasets.

IX. CONCLUSION

This paper has described a system which has been deployed to a cohort of stroke patients in order to monitor and assess their clinical progress via a video game designed to replicate a number of distinct physical movements prescribed by their therapists. During its clinical application, games were distributed to almost 50 patients and data fed back in near real-time to their supervising clinicians. This enabled a far closer supervision of the recovery process than has been practical in the past. The potential for the adoption of Cloud Computing principals has been demonstrated as there are significant data processing, transfer and storage requirements involved throughout the recovery process. Indeed, given the number of stroke patients and the data volumes involved, it could be argued that provisioning such a platform without the innate elasticity and pay-per-use nature of the Cloud would be prohibitively expensive.

Instead of developing a bespoke system, the project opted to build upon the existing e-Science Central platform. The primary benefit of this decision lay in the ready availability of a substantial code base which provided data storage, processing and provenance capture. e-Science Central proved relatively straightforward to deploy in this application and this led to an increase in time available for the development of both the patient and clinician facing websites. The main drawback to this approach, however, lay in the compromises made in terms of the patient management model in order to fit within the simple underlying e-Science Central security model. In the existing e-Science Central security model, there is no concept of multiple owners being responsible for data and artefacts within the system. This made the process of transferring patients between clinicians (a vital requirement in any real-world clinical system) a relatively labour intensive process as there was no mechanism for assigning multiple clinicians to a patient.

ACKNOWLEDGMENT

The authors wish to thank all members of the Limbs Alive project, in particular Janet Eyre, Graham Morgan, Craig Sharp, Martin Scott and Javier Serradilla.

DISCLAIMER

This publication presents independent research commissioned by the Health Innovation Challenge Fund (Grant number HICF 1010 020), a parallel funding partnership between the Wellcome Trust and the Department of Health. The views

expressed in this publication are those of the author(s) and not necessarily those of the Wellcome Trust or the Department of Health.

REFERENCES

- [1] D. of Health, "Progress in improving stroke care," National Audit Office, Tech. Rep., 2010.
- [2] H. T. Hendricks, J. van Limbeek, A. C. Geurts, and M. J. Zwarts, "Motor recovery after stroke: A systematic review of the literature," *Archives of Physical Medicine and Rehabilitation*, vol. 83, no. 11, pp. 1629 – 1637, 2002. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S0003999302002630>
- [3] G. Kwakkel, B. J. Kollen, and R. C. Wagenaar, "Therapy impact on functional recovery in stroke rehabilitation: A critical review of the literature," *Physiotherapy*, vol. 85, no. 7, pp. 377 – 391, 1999. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S0031940605671982>
- [4] B. H. Dobkin, "Rehabilitation after stroke," *New England Journal of Medicine*, vol. 352, no. 16, pp. 1677–1684, 2005, PMID: 15843670. [Online]. Available: <http://dx.doi.org/10.1056/NEJMc043511>
- [5] G. Kwakkel, B. J. Kollen, J. van der Grond, and A. J. Prevo, "Probability of regaining dexterity in the flaccid upper limb: impact of severity of paresis and time since onset in acute stroke," *Stroke*, vol. 34, no. 9, pp. 2181–2186, Sep 2003.
- [6] G. Kwakkel, "Impact of intensity of practice after stroke: issues for consideration," *Disabil Rehabil*, vol. 28, no. 13-14, pp. 823–830, 2006.
- [7] J. Shi, Y. Cheng, J. Serradilla, G. Morgan, C. Lambden, G. Ford, C. Price, H. Rodgers, T. Cassidy, L. Rochester, and J. Eyre, "Evaluating functional ability of upper limbs after stroke using video game data," in *Brain and Health Informatics*, ser. Lecture Notes in Computer Science, K. Imamura, S. Usui, T. Shira, T. Kasamatsu, L. Schwabe, and N. Zhong, Eds. Springer International Publishing, 2013, vol. 8211, pp. 181–192. [Online]. Available: http://dx.doi.org/10.1007/978-3-319-02753-1_18
- [8] H. Hiden, S. Woodman, P. Watson, and J. Cala, "Developing cloud applications using the e-Science Central platform," *Philos Trans A Math Phys Eng Sci*, vol. 371, no. 1833, p. 20120085, Jan 2013.
- [9] P. Watson, H. Hiden, and S. Woodman, "e-science central for carmen: science as a service," *Concurrency and Computation: Practice and Experience*, vol. 22, no. 17, pp. 2369–2380, 2010. [Online]. Available: <http://dx.doi.org/10.1002/cpe.1611>
- [10] J. Cala, H. Hiden, S. Woodman, and P. Watson, "Cloud computing for fast prediction of chemical activity," *Future Generation Computer Systems*, vol. 29, no. 7, pp. 1860 – 1869, 2013. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S0167739X13000253>
- [11] H. Hiden, S. Woodman, P. Watson, M. Catt, M. Trenell, and S. Zhang, "Improving the scalability of movement monitoring workflows: An architecture for the integration of the hadoop file system into e-science central," in *Proceedings of the 1st workshop on Digital Research*, 2012.
- [12] S. Woodman, H. Hiden, P. Watson, and P. Missier, "Achieving reproducibility by combining provenance with service and workflow versioning," in *Proceedings of the 6th workshop on Workflows in support of large-scale science*, ser. WORKS '11. New York, NY, USA: ACM, 2011, pp. 127–136. [Online]. Available: <http://doi.acm.org/10.1145/2110497.2110512>
- [13] M. Brady, D. Gavaghan, A. Simpson, M. M. Parada, and R. Highnam, *eDiamond: A Grid-Enabled Federated Database of Annotated Mammograms*. John Wiley and Sons, Ltd, 2003, pp. 923–943. [Online]. Available: <http://dx.doi.org/10.1002/0470867167.ch41>
- [14] R. Ananthakrishnan, K. Chard, I. Foster, and S. Tuecke, "Globus platform-as-a-service for collaborative science applications," *Concurrency - Practice and Experience*, 2014.
- [15] "Teledicom," <http://www.teledicom.pl/>.
- [16] J. Austin, R. Davis, M. Fletcher, T. Jackson, M. Jessop, B. Liang, and A. Pasley, "Dame: Searching large data sets within a grid-enabled engineering application," *Proceedings of the IEEE*, vol. 93, no. 3, pp. 496–509, 2005.
- [17] M. Fletcher, T. Jackson, M. Jessop, B. Liang, and J. Austin, "The signal data explorer: a high performance grid based signal search tool for use in distributed diagnostic applications," in *Cluster Computing and the Grid, 2006. CCGRID 06. Sixth IEEE International Symposium on*, vol. 1, May 2006, pp. 8 pp.–224.
- [18] D. Webster and O. Celik, "Systematic review of kinect applications in elderly care and stroke rehabilitation," *Journal of NeuroEngineering and Rehabilitation*, vol. 11, no. 1, p. 108, 2014. [Online]. Available: <http://www.jneuroengrehab.com/content/11/1/108>
- [19] N. Borghese, M. Pirovano, R. Mainetti, and P. Lanzi, "An integrated low-cost system for at-home rehabilitation," in *Virtual Systems and Multimedia (VSM), 2012 18th International Conference on*, Sept 2012, pp. 553–556.
- [20] S. Barreca, C. Gowland, P. Stratford, M. Huijbregts, J. Griffiths, W. Torresin, M. Dunkley, P. Miller, and L. Masters, "Development of the chedoke arm and hand activity inventory: theoretical constructs, item generation, and selection," *Topics in stroke rehabilitation*, vol. 11, no. 4, pp. 31–42, 2004.
- [21] J. Shi, Y. Cheng, J. Serradilla, G. Morgan, C. Lambden, G. Ford, C. Price, H. Rodgers, T. Cassidy, L. Rochester, and J. Eyre, "Evaluating functional ability of upper limbs after stroke using video game data," in *Brain and Health Informatics*, ser. Lecture Notes in Computer Science, K. Imamura, S. Usui, T. Shira, T. Kasamatsu, L. Schwabe, and N. Zhong, Eds. Springer International Publishing, 2013, vol. 8211, pp. 181–192. [Online]. Available: http://dx.doi.org/10.1007/978-3-319-02753-1_18
- [22] P. Periorellis, N. Cook, H. Hiden, A. Conlin, M. D. Hamilton, J. Wu, J. Bryans, X. Gong, F. Zhu, R. Smith, P. Watson, and A. R. Wright, "Gold infrastructure for virtual organizations," *Concurrency and Computation: Practice and Experience*, vol. 20, no. 11, pp. 1273–1288, 2008. [Online]. Available: <http://dx.doi.org/10.1002/cpe.1352>
- [23] J. H. Saltzer and M. D. Schroeder, "The protection of information in computer systems," *Proceedings of the IEEE*, vol. 63, no. 9, pp. 1278–1308, 1975.
- [24] A. R. Fugl-Meyer, L. Jääskö, I. Leyman, S. Olsson, and S. Steglind, "The post-stroke hemiplegic patient. 1. a method for evaluation of physical performance," *Scandinavian journal of rehabilitation medicine*, vol. 7, no. 1, pp. 13–31, 1974.
- [25] Z. S. Nasreddine, N. A. Phillips, V. Bédirian, S. Charbonneau, V. Whitehead, I. Collin, J. L. Cummings, and H. Chertkow, "The montreal cognitive assessment, moca: a brief screening tool for mild cognitive impairment," *Journal of the American Geriatrics Society*, vol. 53, no. 4, pp. 695–699, 2005.
- [26] R. W. Bohannon and M. B. Smith, "Interrater reliability of a modified ashworth scale of muscle spasticity," *Physical Therapy*, vol. 67, no. 2, pp. 206–207, 1987. [Online]. Available: <http://ptjournal.apta.org/content/67/2/206.abstract>
- [27] R. C. Oldfield, "The assessment and analysis of handedness: the edinburgh inventory," *Neuropsychologia*, vol. 9, no. 1, pp. 97–113, 1971.
- [28] T. Brott, H. Adams, C. P. Olinger, J. R. Marler, W. G. Barsan, J. Biller, J. Spilker, R. Holleran, R. Eberle, and V. Hertzberg, "Measurements of acute cerebral infarction: a clinical examination scale," *Stroke*, vol. 20, no. 7, pp. 864–870, 1989.